Accounting for ocean and seabed variability in oceanic waveguide parameter estimation

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LONG-TERM GOALS

The long-term objective of this work is to develop methods for rapid assessment of seabed variability combined with detailed localized geoacoustic inversions to characterize the bottom for shallow-water environments. Consideration is given to spatial and temporal variability of water column properties common to shallow-water environments and their impact on inversion results. Advances made in the work will contribute to development of unified ocean/ seabed/ acoustic models and improved prediction capabilities for USW tactical decision aids.

OBJECTIVES

The objective of this research is to expand our understanding of propagation in shallow waters by incorporating high-resolution measurements of both the acoustic field and the ocean environment. The immediate goals of the proposed work are to address research issues relating to parameter estimation derived from acoustic field measurements in shallow water. Parameters of interest include seabed properties (sound speed, density, attenuation) and morphology along with source location. Issues to be addressed include: parameter estimation for geospatially varying bathymetry and sediments; the impact of water column variability on geoacoustic inversion; and the effects of Doppler shift in a waveguide on acoustic measurements and inversion. A particular goal is a comparison of inversion results based on modal eigenvalue estimates and modal dispersion obtained using different co-located data sets.

APPROACH

The approach is focused on analysis of both low-frequency acoustic and high-resolution oceanographic data collected during the Modal Inversion Methods Experiments (MIME) conducted August 2006. MIME was a component of the ONR Shallow Water 06 (SW06) experiment. Acoustic data were collected along synthetic apertures created by a towed source emitting low-frequency, continuous wave (cw) tones (50,75,125, and 175 Hz) and

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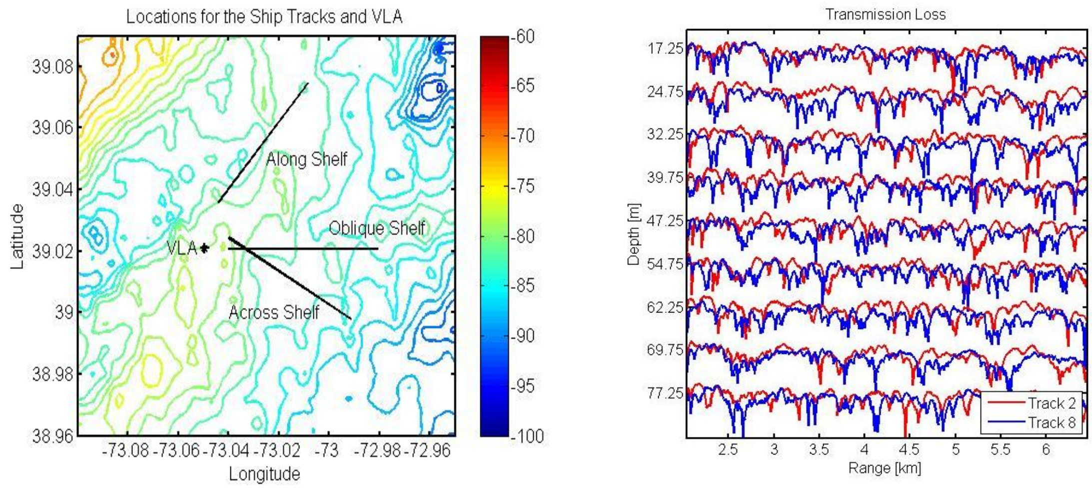

Fig. 1 (Left Panel) Radial tracks along which towed cw data were collected. (Right Panel) Magnitude of pressure fields (50 Hz) measured at all depths on the VLA for Track 2 and Track 8 oriental along the shelf. Track 2 and Track 8 data were collected 5 hours apart and have distinctly different modal interference patterns due to different oceanographic conditions.

for a stationary source transmitting a broadband signal with 250 Hz bandwidth. The acoustic data were measured on a fixed combined vertical/horizontal line array[1]. The magnitude of the acoustic pressure fields for a 50 Hz cw signal measured at all depths on the receive array for the source towed away from the VLA on a radial parallel to the shelf break (Along Shelf) are shown in Fig. 1. The data, corresponding to the 2^{nd} and 8^{th} tracks collected on the same radial were collected 5 hours apart. Using techniques based on the short time Fourier transform, these complex pressure field data are transformed to the horizontal wave number domain. Individual values of horizontal wave numbers associated with peaks in the horizontal wave number spectrum correspond to propagating normal modes and are used as input data for geoacoustic inversion.

Analysis of the SW06 data seeks solutions to the geoacoustic inversion problem which are optimized for both efficiency and accuracy. Emphasis will be placed on developing methods capable of accounting for range-dependence in the seabed that is both directly measurable, such as bathymetry, and unknown, such as that due to intrusions or layer pinching. To explore range dependence, investigation and application of high-resolution wave number estimation techniques [2] will continue. Using wave number information as data, geoacoustic parameter estimates will be sought and compared (for both accuracy and algorithm speed) using linear and non-linear approaches. In addition, to improve the depth resolution of perturbative inversion approaches based on *regularization*, an approach is being pursued which allows for discontinuities in the sediment sound speed profile at interfaces. LFM data collected during SW06 will be analyzed in collaboration with S.D. Rajan and results compared for co-located experiments. Additional areas of research based on analysis of the collected data sets include addressing the impact of watercolumn variability on wave number estimation [3], development of an exact inversion algorithm based on discrete reflection coefficient data obtained from wave number estimates, and a source depth discrimination tool based on the distribution of energy in horizontal wave number spectra.

WORK COMPLETED

The experimental work described for SW06 was completed in August 2006. During the experiment, this project was allocated 36 hours (12 hours each day 4-6 August, 2006) for acoustic transmissions. At the conclusion of the experiment, 34 hours of data were collected. Over 24 hours of towed cw data were collected along 3 different radials. Tow speeds ranged between 2 and 10 knots. The remaining data were LFMs. LFM data were collected for over 25 different stations on a circle 15 km from the VLA. The acoustic data were retrieved from the VLA/HLA, backed up, and archived for distribution by WHOI. The data were received by the author in December 2006. Algorithms for reducing the raw data to a usable form have been completed. Specific coding has been implemented for demodulating the full time series data into the respective single frequency bands and merging with the spatial track data. Particular care has been to accounting for Doppler shift and spread induced by the moving source to maximize fidelity of the demodulated data. The resulting synthetic aperture data are thus reduced to complex pressure as a function of range from the VLA at each of the transmitted frequencies. Code has also been written to produce spatial representations of the sound velocity field in the water column over each of the acoustic track segments.

RESULTS

Range-dependent values of horizontal wave numbers were determined for four frequencies along the three radial tracks indicated in the left panel of Fig. 1. Spatial variability in the sediments combined with spatiotemporal variability in the water column resulted in the highly variable modal interference patterns shown in the right panel of Fig. 1. However, the experiments were designed to make measurements over the same track several times over the course of a day. Thus, observed differences in the acoustic fields measured over the day could be attributed to temporal changes in oceanographic conditions. These measurements provided a great deal of insight into the effects on water-column variability on the propagating field and in particular on the modal content. For example, range-dependent wave number estimates for a subset of modes are shown in Fig. 2 for the track 2 and track 8 data shown above. These data were obtained for the pressure field propagating over the same ocean bottom, but separated in time by 5 hours. In the bottom left panel the range dependence in the estimate of the first modal wave number is clearly shown. This effect is not observed in the bottom left panel for data taken 5 hours earlier. Referring to the upper panel, this result can be interpreted by a shift to the right on the horizontal wave number representing the upper limit k_{max} for the trapped modes. In effect, this upper bound and the lowest order mode that tracks it is responding to a change in the sound speed minimum that occurs in the water column as a function of range. Temperature data converted to sound speed taken at the source location during the source tows confirm this result where a gradual cooling of the water column was observed over the course of the day at the far end of the track. This cooling resulted in the dramatic change in modal interference patterns between measurements made early and later in the day. At the other end of the wave number spectrum, changes in the lower bound and high-order wave numbers are associated with changes with range of the sediment properties.

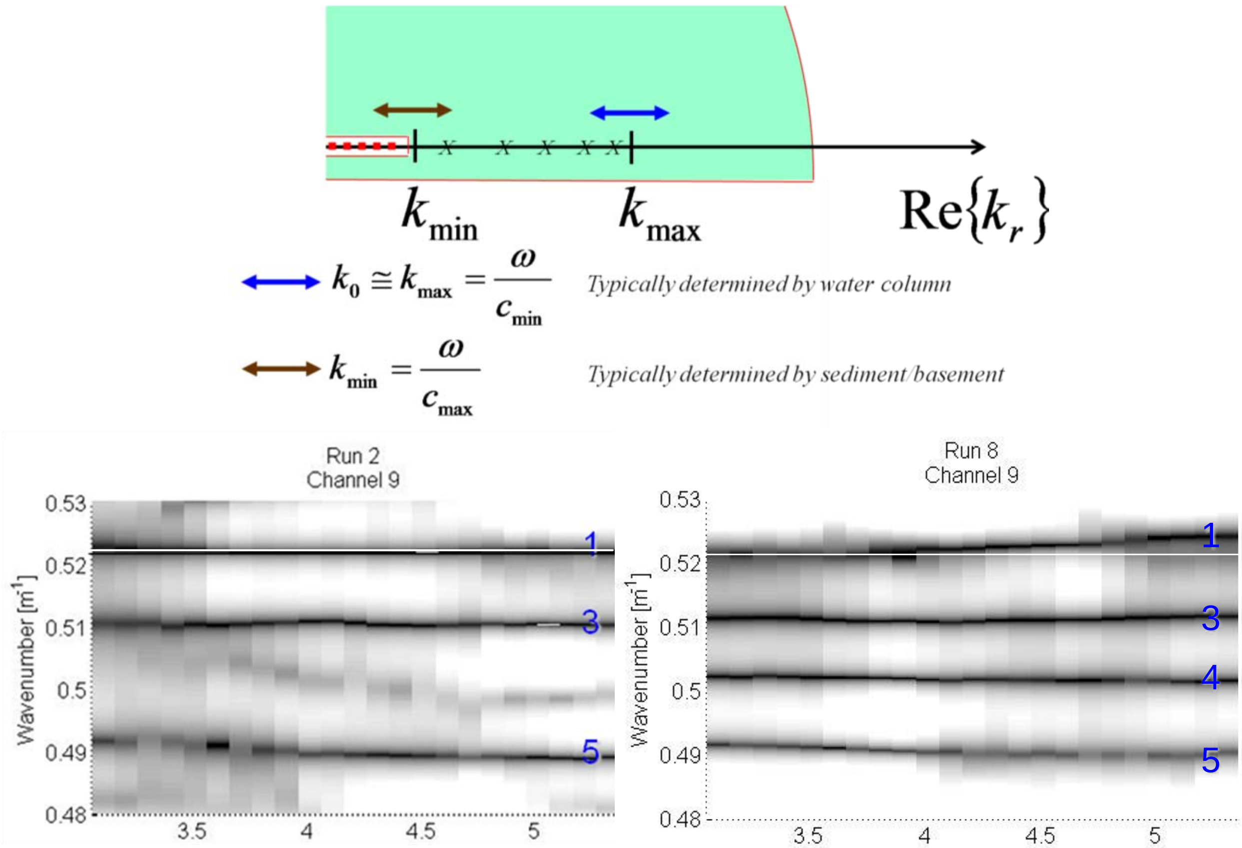

Fig. 2 (Top Panel) Schematic representation of water column and sediment properties on wave number spectrum for trapped modes. Upper limit is typically determined by water column properties and lower limit defined by seabed properties. (Lower Right Panel) Range-dependent wave number estimates for track 2 pressure field shown in Fig. 1. (Lower Right Panel) Range-dependent wave number estimates for track 8 data measured 5 hours later when significant cooling of the water column was observed at the far end of the track. Notice how the wave number for mode 1 increased with range in response to the lower sound speed in the water column at far ranges.

This interpretation of range-dependent wave number estimates provides a means for understanding the independent effects of water column and sediment range dependence on the propagating modal field. Thus, using the wave number estimates at each range as input to a linear inversion algorithm based on qualitative regularization, local estimates of the depth dependent sound speed profile in the sediment were obtained. These results are an improvement to range-independent result reported recently [4] where the low-speed layer was not resolved. Based on high-resolution CHIRP seismic data collected in the region of the tracks, a three-dimensional sediment sound speed model was constructed for the area. Sediment sound speeds within the layers were filled in based on the range-dependent inversion results for the three track lines. The inversion results along the tracks produced consistent results for the sound speeds in the different layers allowing them to be averaged to create the three-dimensional model. For the area nearest the VLA the sediments are represented by two sediment layers over a half-space. Full details of the inversion results and evaluation can be found in Ref. [5]. In addition to inverting for range-dependent sediment properties, the range-dependent wave number data and subsequent

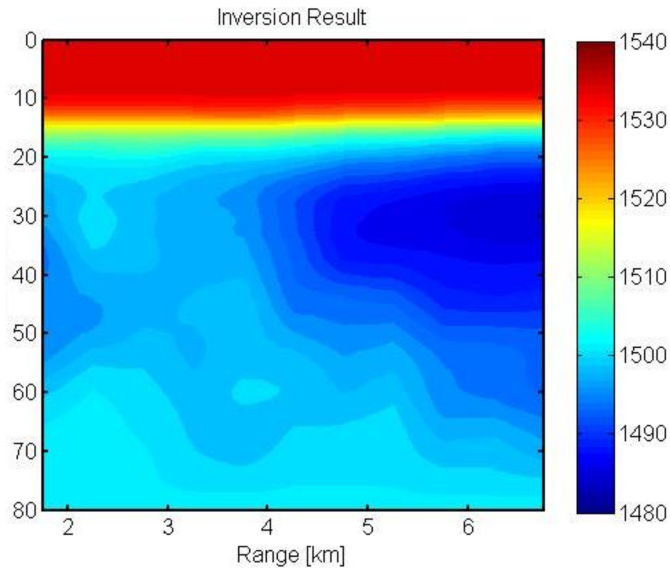

Fig.3 Inversion result for water column sound speed obtained from range-dependent wave number estimates of track 8 data. A general cooling of the water column at the far end of the track can be seen as indicated by the lower sound speed in that region.

interpretation allowed for estimation of range-dependent water column sound speed properties. Fig. 3 shows water column sound speed inferred from range-dependent wave number data for the track 8 data which is in good agreement with measured data.

In addition to inversion based on model eigenvalues obtained from narrowband data, inversion was carried out using LFM data collected during SW06. Based on modal travel time differences estimated from data measured for multiple source receiver positions, geoacoustic inversion for sediment compressional wave speeds was carried out for six regions defining the area between the source locations and the receiver array. The source positions were in an area 15 km to the NorthEast of the VLA. Each of the six regions was characterized by a single sediment sound speed resulting from the inversion algorithm. Results from this analysis are detailed in Ref [6]. Later analysis was applied to source locations to the South of the VLA. Sound speed in the sediment estimated for the source located both north and south of the array is shown in Fig. 4 indicating spatial variability in the region. Although not providing the same spatial resolution as the narrow band inversion results discussed previously, the broadband results showed the same gross features as the narrowband results. In particular, based on the inversion results and consistent with the previous results, the region was characterized by a low-speed sound layer. For the region where the narrowband and broadband data were co-located, the range-averaged sediment sound speed profiles show good qualitative agreement between the two results, particularly in estimating the extent of the low speed layer.

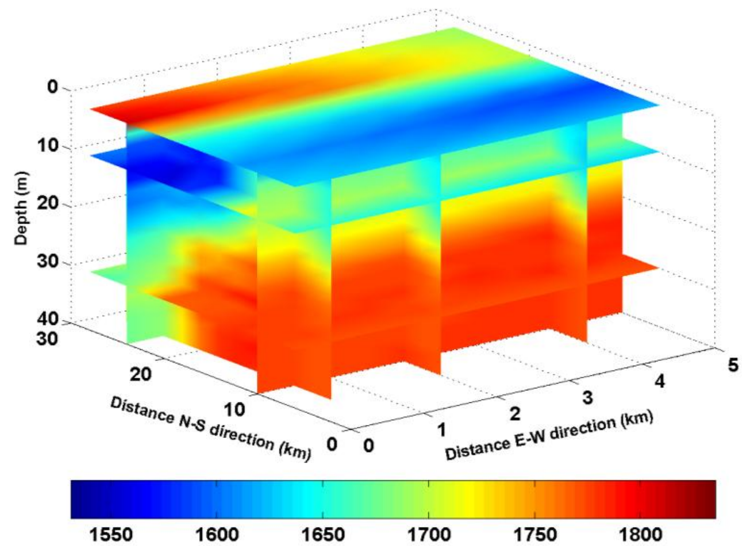

Fig. 4 Sediment sound speed inferred from modal travel time data for the source located 15 km from the array. The inversion results indicate the spatial variability of the sediment sound speed in the region.

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IMPACT/APPLICATIONS

The application of these results is for geoacoustic inversion in range-dependent shallow water regions. The results are directed to suggest ways to account for and deal with the variability inherent in the watercolumn in shallow regions. In addition, the high-resolution methods reduce the apertures required to extract modal information resulting in more localized inversion results.

RELATED PROJECTS

This work was a component of SW06. The approaches being developed recognize the complexities of shallow water waveguide environments and seek to account for them. Data and results from these experiments will be shared with and compared with those of other participating PIs. In addition, it is anticipated that the towed CTD chain data will prove invaluable to interpreting results from this experiment and prove itself to be a worth took for consideration in future experimental efforts.

REFERENCES

[1] A.E.Newhall, T.F. Duda, K. von der Heydt, J.D. Irish, J.N. Kemp, S.A. Lerner, S.P. Libertatore, Y-T Lin, J.F. Lynch, A.R. Maffei, A.K. Morozov, A Shmelev, C.J. Sellers, and W.E. Witzell, Acoustic and Oceanographic Observations and Configuration Information for the WHOI Moorings from the SW06 Experiment, WHOI Technical Report WHOI-2007-04 (May 2007)

[2] K.M. Becker and G.V. Frisk , Evaluation of an autoregressive spectral estimation technique for determining horizontal wave-number content in shallow water", *J. Acoust. Soc. Amer.,* **129**, pp. 1423-1434 (2006)

N.G. Pace and F.B. Jensen (Kluwer, The Netherlands, 2002)
[3] K.M. Becker and G.V. Frisk, “The impact of water column variability on horizontal wavenumber estimation and mode based geoacoustic inversion results”, *J. Acoust. Soc. Am.*, **123** (2), pp. 658-656 (2008)
[4] M.S. Ballard and K.M. Becker, “Geoacoustic inversion on the New Jersey Margin: Along and across the shelf”, J. Acoust. Soc. Am. 123(6), EL141–EL145 (2008)
[5] M.S. Ballard, K.M. Becker, and J.A. Goff, “Geoacoustic inversion on the New Jersey Shelf: Three dimensional sediment model,” IEEE J. Oceanic Eng., 35(1), pp. 28-42 (2010) [published, refereed]
[6] S.D. Rajan and K.M. Becker, “Inversion for range-dependent sediment compressional wave speed profiles from modal dispersion data, ” J. Oceanic Eng., 35 (1), pp. 43-58 (2010) [published, refereed]

PUBLICATIONS

[5] and [6] above

M.S. Ballard and K.M. Becker, “Optimized constraints applied to linearized geoacoustic inverse problems.” accepted to J. Acoust. Soc. of Am. (Sept 2010) [in press, refereed]

M.S. Ballard and K.M Becker, “Inversion for range-dependent water column sound speed profiles on the New Jersey shelf using a linearized perturbative method”, J. Acoust. Soc. Am., 127(6), pp. 3411-3421 (2010) [published, refereed]

K.M. Becker, "Accounting for water-column variability in shallow-water waveguide characterizations based on modal eigenvalues," Proceedings of the 2nd International Conference on Shallow Water Acoustics, Shanghai, China, Sept. 2009. (AIP Press 2010) [published]

HONORS/AWARDS/PRIZES

In December, 2009 Megan S. Ballard was awarded the Ph.D. Acoustics by the Pennsylvania State University. Her thesis was based on this research and is titled: „Optimized Contraints for the Linearized Geoacoustic Inverse Problem’